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APPLICATION OF A SPECTRUM ANALYZER IN FORECASTING OCEAN SWELL IN SOUTHERN CALIFORNIA COASTAL WATERS

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Richard Frank, Administrator

NATIONAL WEATHER SERVICE
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This Technical Memorandum has been reviewed and is approved for publication by Scientific Services Division, Western Region.

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APPLICATION OF A SPECTRUM ANALYZER IN FORECASTING OCEAN SWELL IN SOUTHERN CALIFORNIA COASTAL WATERS

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ABSTRACT. The definitions and concepts of spectral ocean wave forecasting methods are reviewed and applied to the interpretation of trace records of the Snodgrass Spectrum Analyzer. Proper interpretation of the trace enables the prediction of arrival time and size of heaviest surf. Tables derived from the Neumann Spectrum are fitted to the eight frequency channels of the analyzer and used to construct a hypothetical whole spectrum from a partially arrived swell spectrum. Case studies of a North Pacific winter storm, an Eastern Pacific Hurricane, and a Southern Hemisphere storm are made.

I. INTRODUCTION

The significance of ocean swell as a warning of approaching heavy swell or storms themselves has long been recognized. Attempts to quantify this technique were summarized by Munk [1]. In 1970 a wave recording system was installed at Los Angeles Weather Service Forecast Office (WSFO) for this purpose. The sensor was located off Huntington Beach (the specifications on the system are included in Reference 5). The recording system measures ocean surface height through pressure fluctuations of a water column about fifty feet below mean sea level on Platform Eva. The fluctuations are converted to electrical modulations which are sent to the forecast office and analyzed by analog computer. The data sent does not include the very short and very long waves whose amplitudes are often confused with noise. The data received are broken down into eight channels by filters using harmonic analysis. These channels are listed in Figure 1. Filter one, with a 25-second period, and filter eight with a 12-second period, respectively, mark the beginning of significant long wave forerunner energy and the usual cutoff between sea and swell. The filter bands were selected to exhibit a linear time shift in sequence as swell energy arrives from a distant storm. This way the arrival of subsequent channels can be predicted or the distance from the storm determined by the time interval between sequential activation. The wave record taken every 6 hours or so is used to determine the current sea state for verifying the forecasts. This study applies existing spectral wave theory concepts to the analyzer output to help interpret the trace. Important information about the generating storm can be determined from the trace behavior which will help predict the swell. Careful monitoring and trace interpretation together with analyzing ocean surface weather maps, tropical storm bulletins and satellite pictures will assure accurate and timely forecasts of significant surf.

II. CONCEPTS OF SEA STATE FORECASTING METHODS

A. Wave Characteristics and Models.

The sea surface at any point is a combination of many waves in various stages of development and decay. A wind wave forms as energy from the moving air is transferred to the denser ocean surface. The greater the wind velocity (V), the greater the wave height (H) will be which is the vertical distance from trough to crest of the wave. Gravity (g) is the force which causes propagation. The energy per unit area (e) of the wave is equal to

$$1/8\ \rho g H^2 \text{ gm cm/sec}^2.* \qquad \text{eq. (1)}$$

Energy is transferred to the water when the wind speed exceeds the propagation speed of the wave. The propagation speed of the wave is a function of its length (L) which is the horizontal distance between successive troughs or crests. This distance has a stability relationship to the height. Waves grow in length and height reaching a height limit first. The wave period (T) is the time required for a wave length to pass a given point at sea. Frequency (f) is the number of wave forms passing a stationary point per unit time; in other words the inverse of T. The wave velocity

$$V = gT/2\pi \qquad \text{eq. (2)}$$

when not affected by the ocean bottom. Waves of different length travel at different speeds so that waves of different sizes constantly combine and recombine in a constantly changing interference pattern.

The sinusoidal wave from has been used as a model for most ocean wave research and forecast method development. A popular method was developed using a singular wave as a model.** A more realistic model uses sophisticated mathematical methods to represent the ocean surface; a summation of many small sinusoidal waves of different amplitudes and periods. The distribution of amplitudes with respect to frequency is called a spectrum.

B. Wave Generation and Decay.

The area of wave generation is called a fetch. The fetch length is the distance over water that wind speed and direction are essentially constant. The length (F) is a limiting factor on the height of the waves as is the duration (D) of time the wind blows over the fetch length. A fully developed sea defines the maximum height to which wind waves can be generated given a wind speed blowing over a sufficient fetch regardless of duration.

Wave decay occurs when winds weaken or cease or the wave propagates beyond the fetch area. When the wave leaves the fetch area, it becomes swell. A swell group moves with a velocity equal to half the velocity of the wind wave group

$$Cg = 1/2\ V. \qquad \text{eq. (3)}$$

*Where ρ is the specific density of water.

**The definition of a sinusoidal wave form is shown in Figure 2.

The reason commonly given for this is that the leading wave is attenuated by expending some energy in setting the water in motion. The result is that waves continually dissipate at the leading edge of the wave group and a new wave forms at the rear of the group. The distance traveled by the water after leaving the fetch is called the decay distance (d). During decay the apparent wave period increases but the height decreases. This is due to two main processes, wave dispersion and angular spreading. Since the waves of different lengths move at different speeds, the energy of a wave group spreads out along its path, the longer waves arriving at the observation point first. The energy also spreads radially covering a larger area with time.

C. Wave Records.

Empirical relationships between fetch conditions, seas, and swell need to be derived through observations if a forecast method is to be developed. Early methods of observations depended on a man's visual determination of the height and period of the sea. Modern methods have employed wave records. A wave record is a continuous recording of the height of the ocean surface or a series of heights taken at equal time intervals. An example is displayed in Figure 3. At least twenty minutes of record is needed to derive meaningful information about wave heights and periods. With data as variable as ocean wave records, statistics must be employed to make order from the chaos. One-third of the highest waves of a given wave group is called the significant wave and is defined by the average of their heights and periods. The assumption is made that variations of the ocean level about the mean level fit the normal or Gaussian distribution. The Gaussian assumption above leads to a Rayleigh distribution for wave heights. With this distribution, the energy of a wave record can be approximated by twice the variance of the values of a digital record. The Gaussian and Rayleigh distributions and properties are displayed in Figure 4.

D. Wave Forecast Methods.

A popular singular wave method was developed by Sverdrup, Munk, and Bretschneider (SMB). Procedures, tables, and example are described in WRTM 51 [4]. Briefly, the method consists of entering graphs with basic input parameters, windspeed, fetch length and duration, and reading off values of significant height and period for the wave leaving the fetch. Another table with decay distance specified gives you the corresponding characteristics of the swell. The speed of this wave is used to determine arrival time of significant energy.

A popular spectral method was developed by Pierson, Neumann, and James (PNJ). Procedures and tables are found in reference [3]. Briefly, the spectrum is estimated from the wind field. The spectrum estimate is then truncated at lower frequency according to the fetch and duration, whichever limiting. The wave energy left in the spectrum is divided into frequency bands and propagated at group velocity to a forecast point. Energy components arriving simultaneously at the point are summed and the sum multiplied by a parameter to account for the angular spreading. Wave characteristics are then related to the energy at a point at any moment in time. A continuous forecast of wave height and period is provided. In the case of waves arriving from more than one fetch, the energy associated with the various fetches is added together.

III. INTERPRETING THE SPECTRUM ANALYZER TRACE

A. Characteristics of the Theoretical Spectrum.

The mathematical model used to describe the fully arisen state of the sea in the PNJ method is the Neumann function:

$$[A(\sigma)]^2 = C \times \frac{\pi}{2} \times \sigma^{-6} \times \exp\ (-2\ g^2\ \sigma^{-2}\ V^{-2}) \qquad \text{eq. (4)}$$

where $\sigma = 2\pi f$

and A is the wave amplitude for a given frequency f, and C is a constant equal to $3.05 \times 10^4\ cm^2\ sec^{-5}$. This function is displayed for three different windspeeds in Figure 5. Note that the peak extends to lower frequencies at higher values of V. The frequency of maximum energy, f_{max}, is given by the equation:

$$f_{max} = \sqrt{2/3}\ g\ V^{-1}. \qquad \text{eq. (5)}$$

As the spectral energy in a broad band around the frequency of maximum energy increases, the contribution of wave energy at the lower end of the curve near the abscissa becomes less significant. A co-cumulative spectrum displayed in Figure 6 is derived by summing the energy contribution of each frequency beginning at the higher end of the spectrum. The total energy, E, is given by:

$$E = C \times 3\ (\pi/2)^{3/2} \times (V/2g)^5. \qquad \text{eq. (6)}$$

The significant part of the spectrum may be defined as a certain percentage, usually 95%, of the total energy. The lowest significant bound frequency is usually not generated in a real fetch because the duration and length is usually limited in which case this bound is called the cut-off or intersection frequency. Identifying these spectrum properties as the energy arrives at the recording site is the key to interpreting the analyzer trace and forecasting the arrival, magnitude, and abatement of heavy swell.

Tables for interpreting the analyzer trace are displayed in Figures 7a-c. The table in Figure 7a shows the group velocity of each filter which is derived from equations 2 and 3. The fourth column is the minimum fetch intensity needed to activate the specified filter; that is, the velocity needed to make that filter account for greater than 5% of the total energy. The fetch intensity corresponding to a filter containing the maximum energy band is derived from equation 5. The table in 7b presents the Neumann function, equation 4, as a function of the eight analyzer channels and several windspeeds. The values are normalized by dividing the amplitude of the first filter with significant energy. The 7c table shows the filter arrival times at various distances. This table was derived by solving the simultaneous distance equations for the arrival time difference. That is:

$$\Delta t = \frac{R_2 - R_1}{R_1\ R_2} \times D. \qquad \text{eq. (7)}$$

where R is the wave velocity of the respective filters and D is the travel distance. The relationships in these tables can be used to (1) evaluate the effective intensity of a fetch based on the early channels, (2) estimate the decay distance based on the time interval between arriving channels, and (3) estimate the amplitude of the maximum energy channel based on the amplitude ratios of the early filters.

Figure 8 shows an idealized analyzer trace resulting from a 40-knot fetch with an arbitrary duration and decay distance. Estimates of significant swell height or other wave characteristics can be made if it is related statistically to the energy levels of the various filters.

B. Rules for Interpreting the Trace.

When a channel activates, the effective wind of a fully arisen fetch can be estimated by referring to Figure 7a. This estimate in column 4 is a lower bound; that is, winds must be greater or equal to this value if the corresponding channel activates. Using an estimate of fetch intensity, one can determine which channel contains the maximum energy by scanning column 5. If the decay distance is known, the arrival time of waves in the channel with maximum energy can be predicted using Figure 7c.

Example: Channel 3 activates first with significant energy. Then from Figure 7a the average period of the swell is 20 seconds and it was generated in a fetch with an effective windspeed of at least 37 knots. From Figure 7b the total energy from the fully arisen fetch will reach a maximum following the arrival of channel 6 containing maximum energy. Figure 7c shows that channel 6 will arrive approximately 10 hours after channel 3 given a decay distance of 1000 nautical miles.

When two consecutive channels activate successively, the distance to the fetch can be estimated if not already known by referring to Figure 7c.

Example: Channel 3 activates about 3 hours after channel 2. The fetch then is not farther than 1000 nautical miles away. If 12 hours elapsed between the activation of these channels, the fetch would be about 4000 nautical miles away.

When a channel activates very slowly, the fetch is probably very far away. If we assume that the slope activation is determined by the rate at which the widely dispersed energy arrives at the sensor, the distance might be estimated by using this slope. By substituting the velocities of the upper and lower frequencies of the channel band into the equation 7, we can solve for D.

Example: Channel 3 starts and rises to a maximum in 10 hours. The channel width is waves of $.0475 \leq f \leq .0525$ which range in wave group velocities of 32 to 29 knots, respectively. The distance D is:

$$D = 10 \times (29 \times 32)/(32 - 29) = 3093.$$

When two channels activate simultaneously, the swell that is arriving probably has a period midway between the two channels. Eventually the latter channel will emerge as the significant one.

When a channel levels out and the effective wind is known, the energy level of the successive channels can be estimated by referring to Figure 7b.

Example: The fetch intensity is 40 knots and channel 3 levels out at 3 units. Then the level of the maximum channel 5 will be the energy in channel 3 multiplied by the energy ratio between channels 3 and 5 which is:

$$\left(\frac{1.4}{1.0}\right) \times 3 \text{ units} = 4.2.$$

If two channels level out, the ratio of these two channels can be used to estimate the effective wind and thus the energy level of the maximum energy channel by referring to Figure 7b. Example: Channel 2 and 3 level out and their level ratio is 2.0. The fetch intensity is about 35 knots (.6÷.3=2.0). If the relationship between energy levels and wave heights is determined statistically, the wave heights can be predicted also.

When a channel accelerates rapidly, that is much faster than the preceding one, the frequencies arriving are very close to the frequency of maximum energy. Maximum total energy and the heaviest swell is imminent.

When a channel decreases and the maximum channel is known, the abatement of significant energy can be predicted by referring to Figure 7c.

Fluctuating channel levels or nonconsecutive arrival order tends to confuse the forecaster. Swell from different fetches are probably superimposed when the channels seem to act independently. Variable fetch conditions or interference from currents or opposing wind fields can act on various portions of the traveling spectrum.

C. Case Studies.

Three cases are provided to demonstrate how the recorder and analyzer can be, or have been, used. They also illustrate trace characteristics of common storm types.

Midlatitude Storm:

A North Pacific storm the second week of November 1971 provided a case in which the effective wind fetch was nearly stationary with respect to the southern California coast. The circulation of a 978 millibar Gulf of Alaska low dipped south of 40° North and strengthened after it absorbed a vigorous storm from the Bering Sea November 7th. With the long-wave trough position being near 135° West, the storm was directed northeastward to the Pacific Northwest after it had generated a well-developed fetch. The 0600 GMT Pacific analysis November 9, 1971, shows a fetch of adequate duration and length (Figure 9). A forecast for the San Diego area was made using the SMB method and the results are displayed (Figure 10). A PNJ forecast based on same fetch conditions developed later for comparison is also displayed. The prediction called for 4.5 foot significant wave heights arriving around 1000 PST November 11. The worded forecast Tuesday afternoon called for a gradual increase in wave heights up to 5 feet on Thursday. The three hourly energy levels of each channel, the total energy and the observed statistics of a hand analysis of several records are tabulated (Figure 11). Actual activation times are best found looking directly at the trace but this table shows roughly what occurred. If the analyzer were carefully monitored on the 10th, timely updates of the forecast might have been made. Channel 2 activated at 0100 PST on November 10th and by 0600 PST had significant energy. Figure 7a indicates that 42 knots might have been a better wind value to use in the forecast technique but probably with a limited duration time. Referring to Figures 7a and 7b, the forecaster could expect channel 4 to be a maximum but considerable energy would be spread through channels 4 to 6. Using Figure 7c, he could predict that the total energy would be increasing to a maximum after the arrival of channel 6 and would continue at this level until channel 4 decreases. Channel 3 came up 3 hours after channel 2 verifying the estimated 1000 nautical mile decay distance. According to Figure 7c then, channel 4 would arrive 6.2 hours after channel 2 (at 10/0700 PST) and channel 6, 13.5 hours later (at 10/1500 PST). Channel 2 is seen to level out at 5.0 units of energy by 10/0900 PST indicating that channels 4 through 7 are likely to attain 10 units or more if the fetch is fully developed at the assumed windspeed. The tabulated trace shows the successive arrival of channels approximately on schedule with the total energy maximizing at about 10/1800 PST and continuing quite high until 0600 PST on the 11th. The levels expected in channels 5 through 7 were not realized. The decrease of channel 3 after 10/2100 PST cues the successive decrease of energy in the other channels and indicates that the duration of the storm was about 42 hours.

$$(2100 - 0900) \text{ hours} + (1000 \text{ nm}/33.3 \text{ kt}) = 42 \text{ hours.}$$

The wave recorder showed the highest readings between 1800 PST November 10 and 0900 PST November 11. Huntington Beach lifeguards reported 5- to 6-foot breakers with occasional sets to 9 feet. Mission Beach lifeguards reported breakers 5 to 6 feet, and Scripps reported near 6 feet. The forecasters updated the forecast with an earlier arrival time of maximum height waves Wednesday afternoon after waves were reported up to 4 feet. The evidence for updating was available on the analyzer earlier but was not interpreted until the marine forecaster came on duty after the Wednesday morning dissemination time.

Tropical Storm:

Although tropical storms account for a major part of the summer surf, only a small percentage of them cause damaging surf because the duration of the wind over the water is limited due to the rapid westward movement common of these storms. The duration of arriving swell, however, is quite long because the circular fetch generates swell in all directions so that even though the storm is moving with respect to an observation point, the angle from which it comes remains the same. Occasionally the storms turn northeastward; thus, prolonging the duration time to produce much higher swell directed to the California coast. However, when this happens the storms are usually traveling over increasingly colder water and its intensity diminishes. Tropical storm Hyacinth entered the window Thursday afternoon, September 1, 1972. The window is that area of the ocean from which swell energy will arrive at the observation site undeflected by land objects. In this case the window is determined by the coastline of Baja California and the channel islands of southern California. The window for platform Eva includes the radials from 158 to 196°. The abnormally warm sea temperatures of 1972 allowed Hyacinth to turn northeastward on the 4th. The path of this storm is displayed in Figure 12. The forecast Friday morning indicated increasing swell 4 to 5 feet for early Sunday. The forecaster used the SMB charts as a guide. Choosing the parameters to be used in this technique, however, is very subjective for tropical storms. The effective fetch conditions would not be ascertained until the analyzer started to pick up energy. At 0000 PST (9/3/72) Saturday morning, channel 6 activated followed by channel 7 at 0300 PST (9/3/72), see Figure 13. This indicated an effective windspeed of only 26 knots, considerably less than the 80 knots near the center of the storm, and a decay distance of about 1000 nautical miles. Based on this, the forecaster could predict that the energy would increase to a maximum of about 4 units by the time channel 8 levels out 6 hours later 0900 PST (9/3). At 1500 PST (9/3) channels 4 and 5 activated simultaneously arriving from a fetch with winds greater than 30 knots. Based on this, the forecaster could look for a further increase in successive channels early Sunday, but the forecast already adequately described the expected conditions. The increase finally reached channel 7 increasing it from 3 to 4 units, but the total energy did not increase because the levels of the lower channels were beginning to diminish at this time. A consistent decrease in channel 5 was observed at 0600 PST (9/4) Sunday which seemed to indicate the eventual decrease of total energy. The forecast Sunday indicated this trend. However, the storm varied in intensity Sunday and recurved northeastward Monday. With this in mind, the forecaster could not continue the decreasing trend. Fluctuations of the analyzer during this time were difficult to interpret but the energy continued at a fairly high level well into Tuesday without decreasing. During this time, forecasting winds and local sea conditions was the main concern as the storm neared the coast.

Southern Hemisphere Storms.

The analyzer becomes most indispensable in the early detection and prediction of swell energy from the Southern Hemisphere. This is true not only because of the limited coverage and infrequent analyses of the Southern Hemisphere received operationally, but also because it is difficult to assess the effect of interferring wind and current patterns on the wave energy during its long travel. A good case of Southern Hemisphere swell detected on the analyzer occurred in mid-August 1973. The charts received showed a storm developing August 6 through 8 in the southwest Pacific. The strength and shorter distance of the storm gave reason to expect some significant swell from the storm (Figure 14). A quick SMB calculation yielded a prediction of 3.5 foot swell arriving with period 20 seconds on the 14th at 0900 PST. On the 14th at 1800 PST channels 2 through 5 showed gradual increases with slopes typical of a very distant storm (see Figure 15). The low level and slow arrival of this energy make reading the trace difficult in the early stages. Actually the lower channels must have been increasing earlier but too slowly to be detected. The significant energy in channel 2 did indicate a fetch wind of at least 40 knots but the distance in this case is difficult to estimate from the trace. The maximum energy could be expected to attain a level 11 to 14 units with the arrival of channel 7, 38 hours later or 0800 PST the 16th. The channels fluctuated indicating perhaps variations of the storm or more likely, unknown filtering processes. A consistent decrease in channel 2 is noted at 15/18 PST before channel 7 started up. Thus, the duration of the storm has limited the maximum energy in this case. Now the decrease in the other channels is predicted and eventual demise of energy 64 hours later. During this episode, the wave recorder indicated 2 foot swell maximum and the highest breakers recorded were 6 feet at Zuma. Surfers reported later that the breakers they saw on the 16th were the "best" they had seen all summer.

IV. CONCLUSIONS AND SUGGESTED WORK

The preceding cases, although examined in hindsight, demonstrate that the spectrum analyzer fulfills its designed purpose; that is, to predict the arrival of heavy, long-wave energy from great distances. They also show that understanding what trace characteristics represent in terms of changing fetch conditions can help to at least qualitatively update a sea-state and surf forecast. Its value increases for storms at long distances away where the full advantage is made of the rapid forerunning swell energy. Using spectral methods to forecast waves enhances its value because it performs as a verification of the forecast output before empirical formulae is applied. It has been suggested that if wave height estimates can be made from the analyzer trace then quick wave height predictions can be made by linear extrapolation of the channel energy. Computer capability was not available to the investigator so a limited amount of data was analyzed statistically to this end. Simple linear regression was applied to the case study data, however. Correlation coefficients, .89, .87, and .59, were determined for the winter storm, the hurricane and the Southern Hemisphere storm, respectively. These values indicate some promise in the case of relatively nearby storms. Much more data would have to be analyzed to derive anything meaningful. The increase in the number of data buoys in the Pacific could eliminate the need for further investigation of the spectral analyzer in this way. Continuous spectral data from these buoys can be used in the same way, and the relationship between energy and wave height is already empirically determined.

V. REFERENCES

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4. Shields and Burdwell, 1970: Western Region Sea State and Surf Forecaster's Manual, ESSA WBTM WR51.

5. White Instruments, Incorporated, Installing and Operating Model 121, Spectral Analyzer.

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7. Oceanographic Services Sections, Operations Department, Forecasting Ocean Waves and Surf. U. S. Fleet Weather Facility, U. S. Naval Air Station, San Diego, 1970.

8. Kinsman, Blair, 1964: Wind Waves, their Generation and Propagation on the Ocean. Prentice Hall.

9. U. S. Army Coastal Engineering Research Center, 1966: Shore Protection, Planning and Design. Technical Report No. 4, Department of Army Corp of Engineers.

FILTER SPECIFICATIONS

	Type Number	3 dB Band Edges
1.	3616 - 10%, 0.040	.038 & .042 $\pm$ .0004 Hz
2.	3616 - 10%, 0.045	.0428 & .0473 $\pm$ .00045 Hz
3.	3616 - 10%, 0.050	.0475 & .0525 $\pm$ .0005 Hz
4.	3616 - 10%, 0.055	.0523 & .0577 $\pm$ .00055 Hz
5.	3616 - 10%, 0.060	.057 & .063 $\pm$ .0006 Hz
6.	3616 - 10%, 0.065	.0618 & .0683 $\pm$ .00065 Hz
7.	3616 - 10%, 0.070	.0665 & .0735 $\pm$ .0007 Hz
8.	3616 - 10%, 0.080	.076 & .084 $\pm$ .0008 Hz

Gain = 51 dB $\pm$ 1.5 dB, Bandwidth Tolerance $\pm$ 1% f_o

Smoothing Filters

Type Number 3617

Smoothing time constant $\simeq$ 3600 sec

AC/DC conversion gain 1 Vdc/1 Vrms = 1

Figure 1. Filter Specifications.

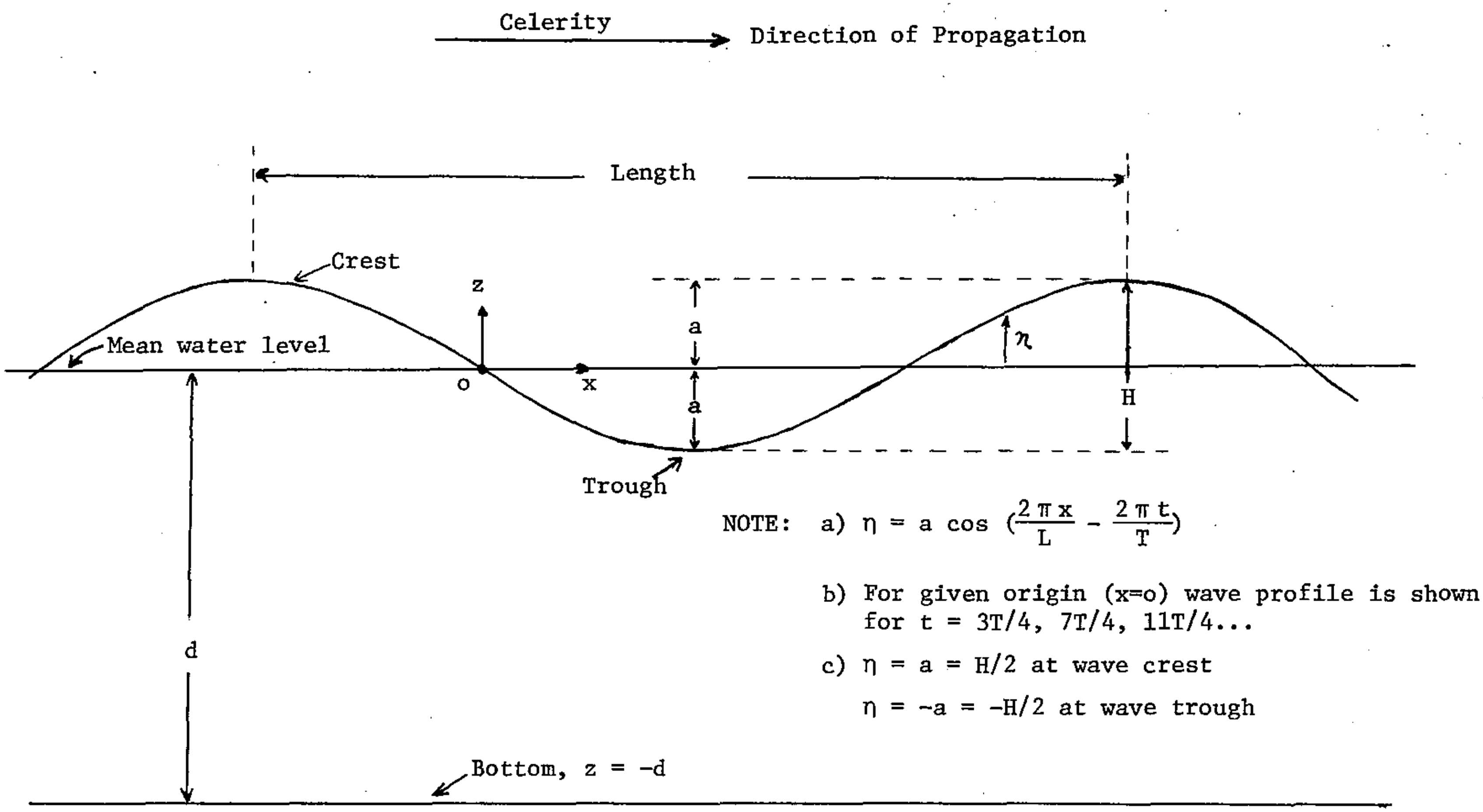


Figure 2. Definition of Terms - Elementary, Sinusoidal, Progressive Wave.

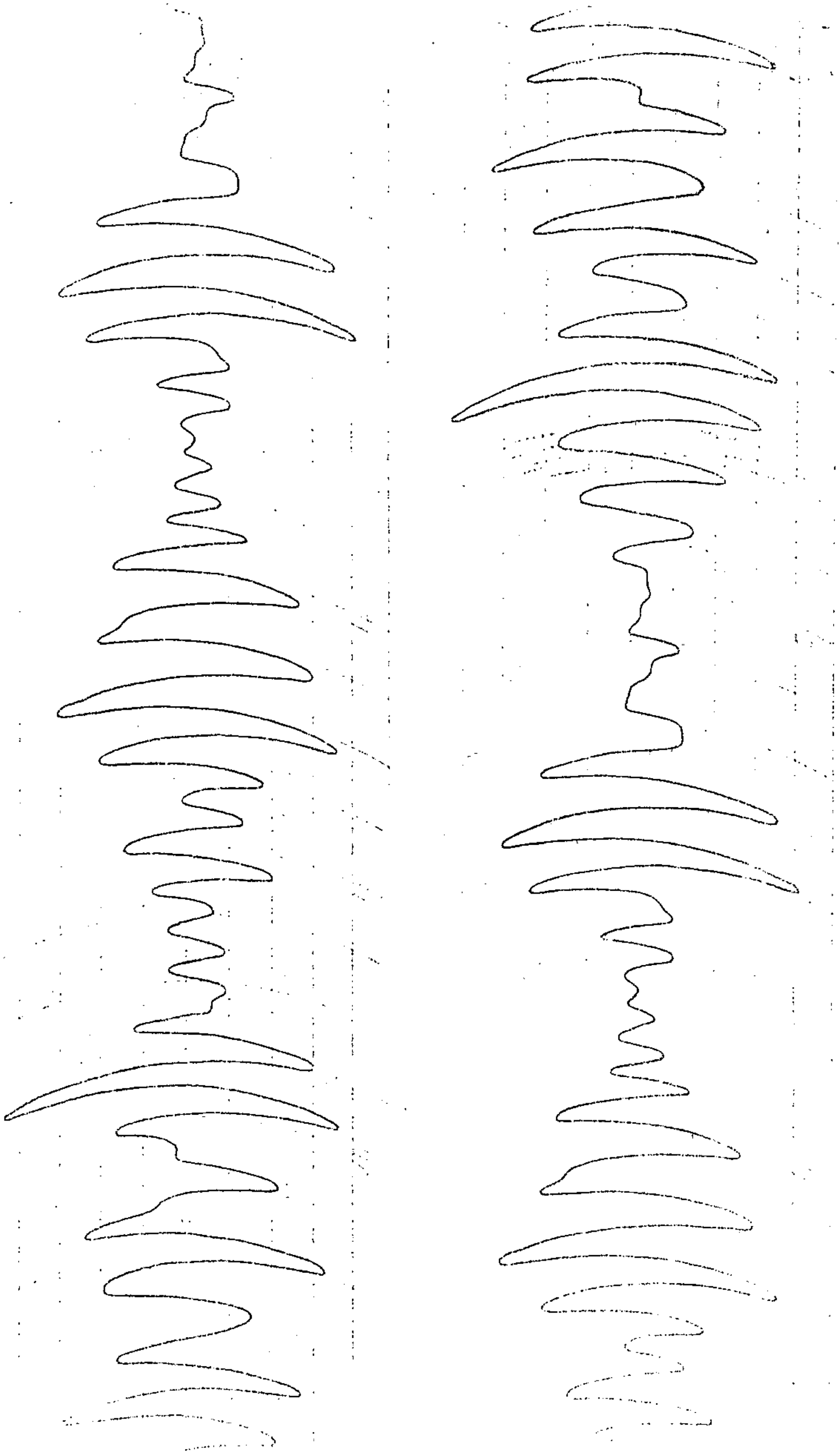
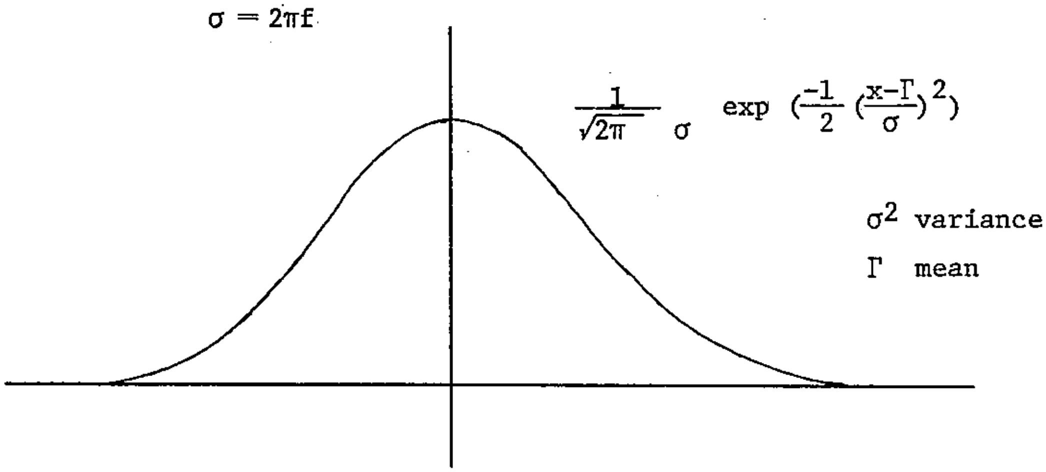
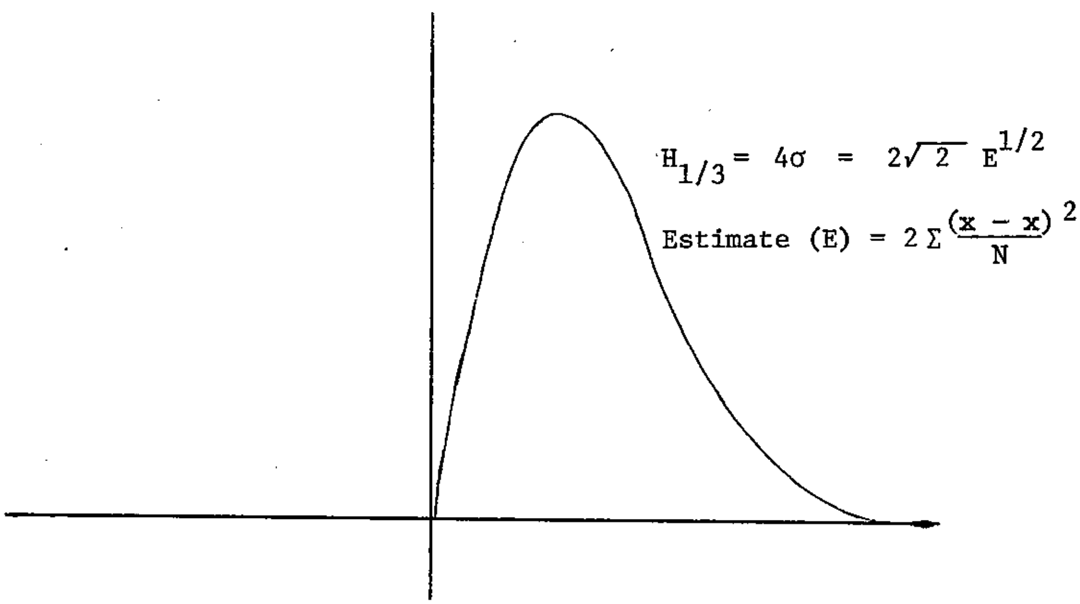


Figure 3. Continuous wave record.

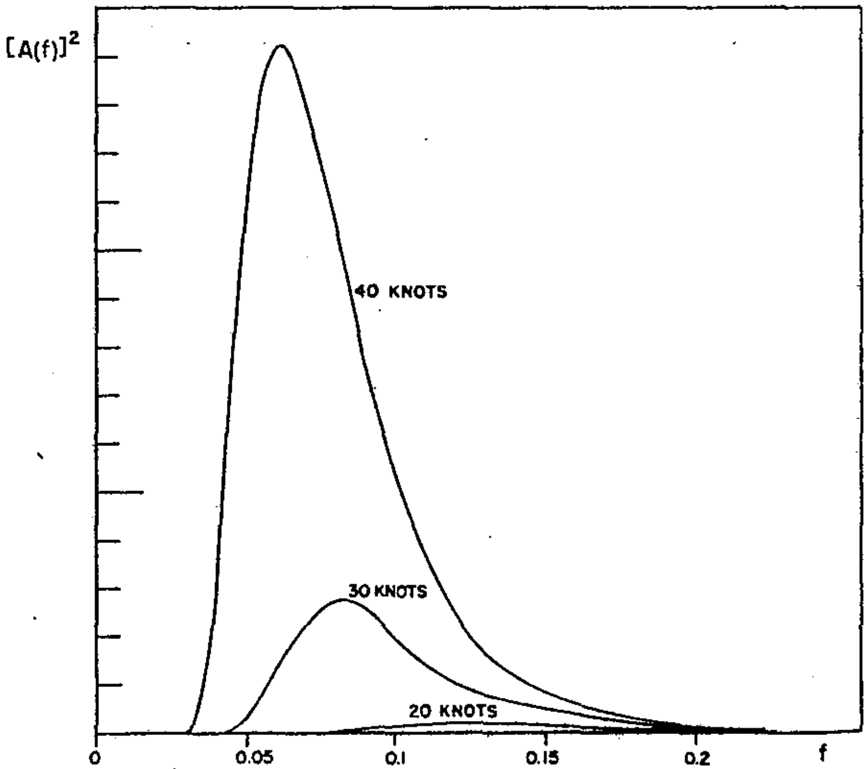


Gaussian Probability Distribution
(the variation of ocean surface about MSL)



Rayleigh Probability Distribution
(Variation of wave heights about the average height)

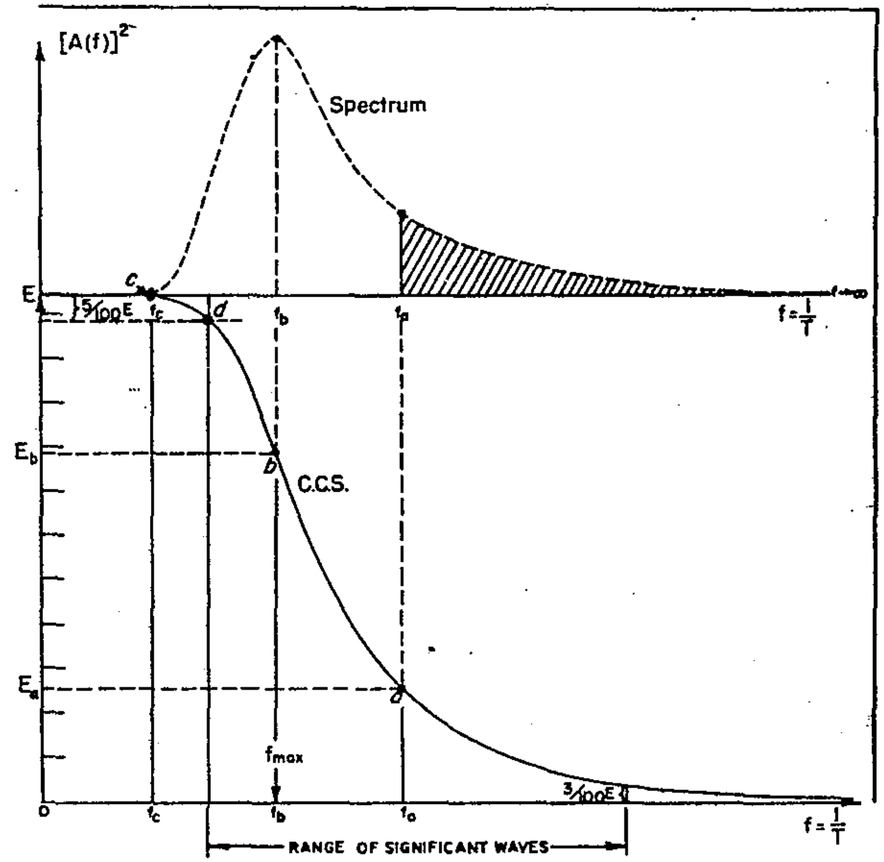
Figure 4. Gaussian and Rayleigh Probability Distribution Graphs.



$$[A(\sigma)]^2 = C\,\frac{\pi}{2}\;\sigma^{-6}\exp\{-2\,g^2\,\sigma^{-2}\,V^{-2}\}$$

$$\sigma = 2\pi f$$

Figure 5. Neumann Spectrum for a few windspeeds.



a cut-off frequency
b maximum frequency
d lowest significant bound

Figure 6. Wave Spectrum and Co-cumulative Spectrum.

FIGURE 7A. WAVES AND FETCH CHARACTERISTICS FOR THE EIGHT FREQUENCY FILTER CHANNELS OF THE SPECTRAL ANALYZER.

FILTER NUMBER	AVERAGE PERIOD (Secs)	GROUP VELOCITY (Kts)	MINIMUM FETCH INTENSITY (Kts)	MAXIMUM FETCH INTENSITY (Kts)
1	25.0	37.9	46	60
2	22.2	33.3	42	54
3	20.0	30.3	37	49
4	18.2	27.6	34	44
5	16.7	25.3	30	40
6	15.4	23.3	26	37
7	14.3	21.7	26	35
8	12.5	18.9	23	32

FIGURE 7B

THEORETICAL CHANNEL ENERGY LEVEL RATIOS WITH RESPECT TO THE LOWEST CHANNEL OF SIGNIFICANT ENERGY

Windspeed

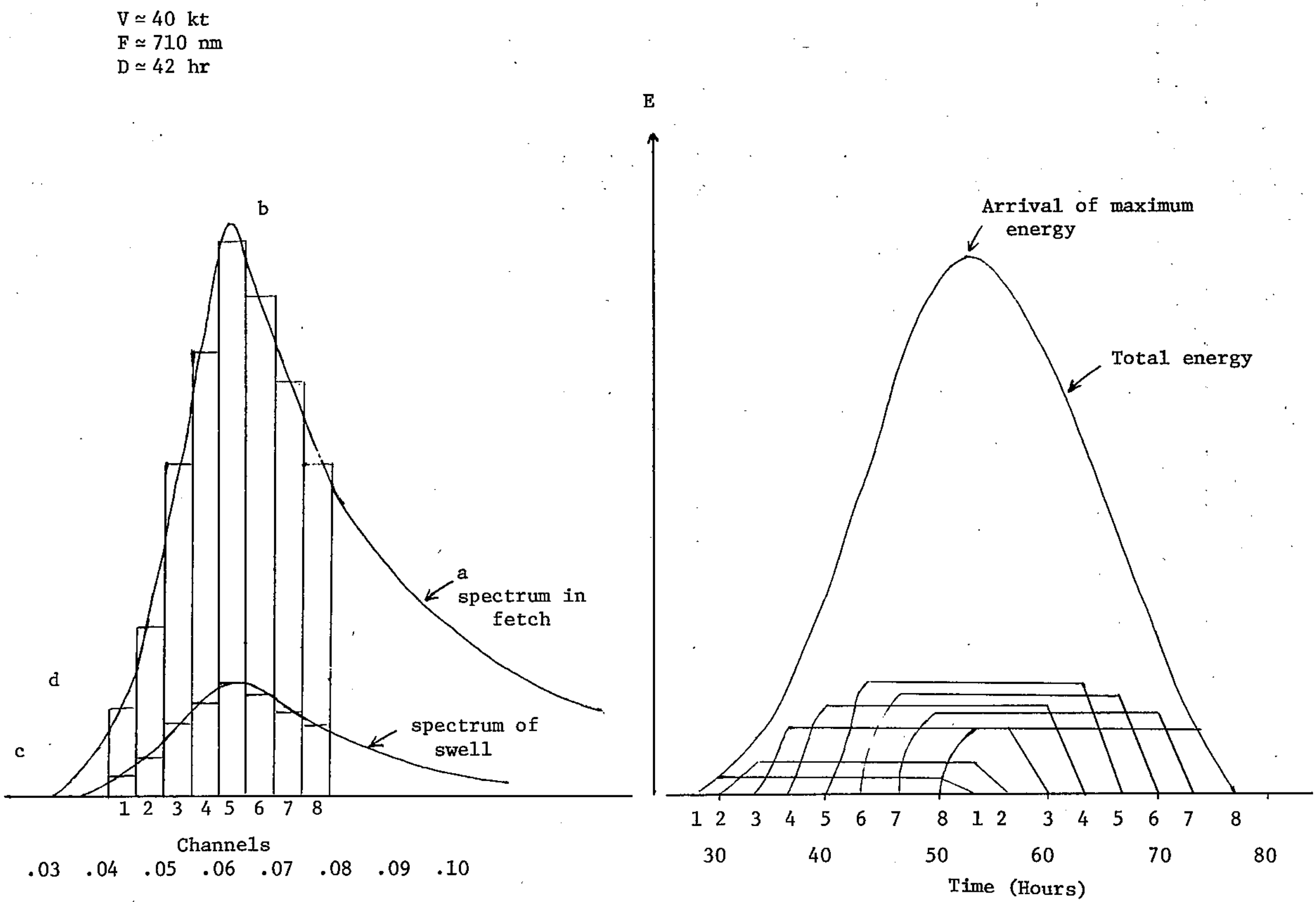
frequency Hz	channel	20	25	30	35	40	45	50	55	60 knots	
.040	1	0	0	0	.1	.3	.6	1.	1.	1.	
.045	2	0	0	.1	.3	.6	1.	1.3	1.1	1.	
.050	3	0	0	.3	.6	1.	1.2	1.4	1.0	.8	
.055	4	0	.2	.6	1.	1.3	1.3	1.3	.9	.7	
.060	5	.1	.5	1.	1.3	1.4	1.3	1.1	.7	.5	
.065	6	.3	1.	1.4	1.5	1.3	1.1	.9	.6	.4	
.070	7	1.	1.7	1.8	1.6	1.2	1.0	.8	.4	.3	
.080	8	4.1	3.1	2.1	1.4	1.0	.9	.5	.3	.2	
		3.8	6.67	3.90	1.34	3.42	7.21	1.31	2.89	5.31	Amplitude of lowest significant channel
		0	1	2	3	3	3	4	4	4	power of ten

FIGURE 7C

WAVE ANALYZER FILTER TIMES (HOURS)

DISTANCE MM	FILTERS 1 to 2	FILTERS 2 to 3	FILTERS 3 to 4	FILTERS 4 to 5	FILTERS 5 to 6	FILTERS 6 to 7	FILTERS 7 to 8
1000	3.6	6.6	9.8	13.1	16.5	19.7	26.5
1500	5.4	9.9	14.7	19.7	24.8	29.5	39.8
2000	7.3	13.2	19.7	26.3	33.0	39.4	53.0
2500	9.1	16.5	24.6	38.8	41.3	49.2	66.3
3000	10.9	19.8	29.5	39.4	49.6	59.0	79.5
3500	12.8	23.2	34.5	46.0	57.9	69.0	92.9
4000	14.6	26.5	39.4	52.6	66.2	78.8	106.1
4500	16.4	29.8	44.3	59.2	74.4	88.7	119.4
5000	18.3	33.1	49.3	65.7	82.7	98.5	132.7
5500	20.1	36.4	54.2	72.3	91.0	108.4	145.9
6000	21.9	39.7	59.1	78.9	99.2	118.2	159.2
6500	23.7	43.0	64.0	85.4	107.5	128.0	172.4
7000	25.5	46.3	68.9	92.0	115.7	137.9	185.6
7500	27.3	49.6	73.8	98.5	124.0	147.7	198.9
8000	29.1	52.9	78.8	105.1	132.2	157.6	209.2

Figure 8. Ideal spectrum analyzer trace and corresponding Neumann spectrum.



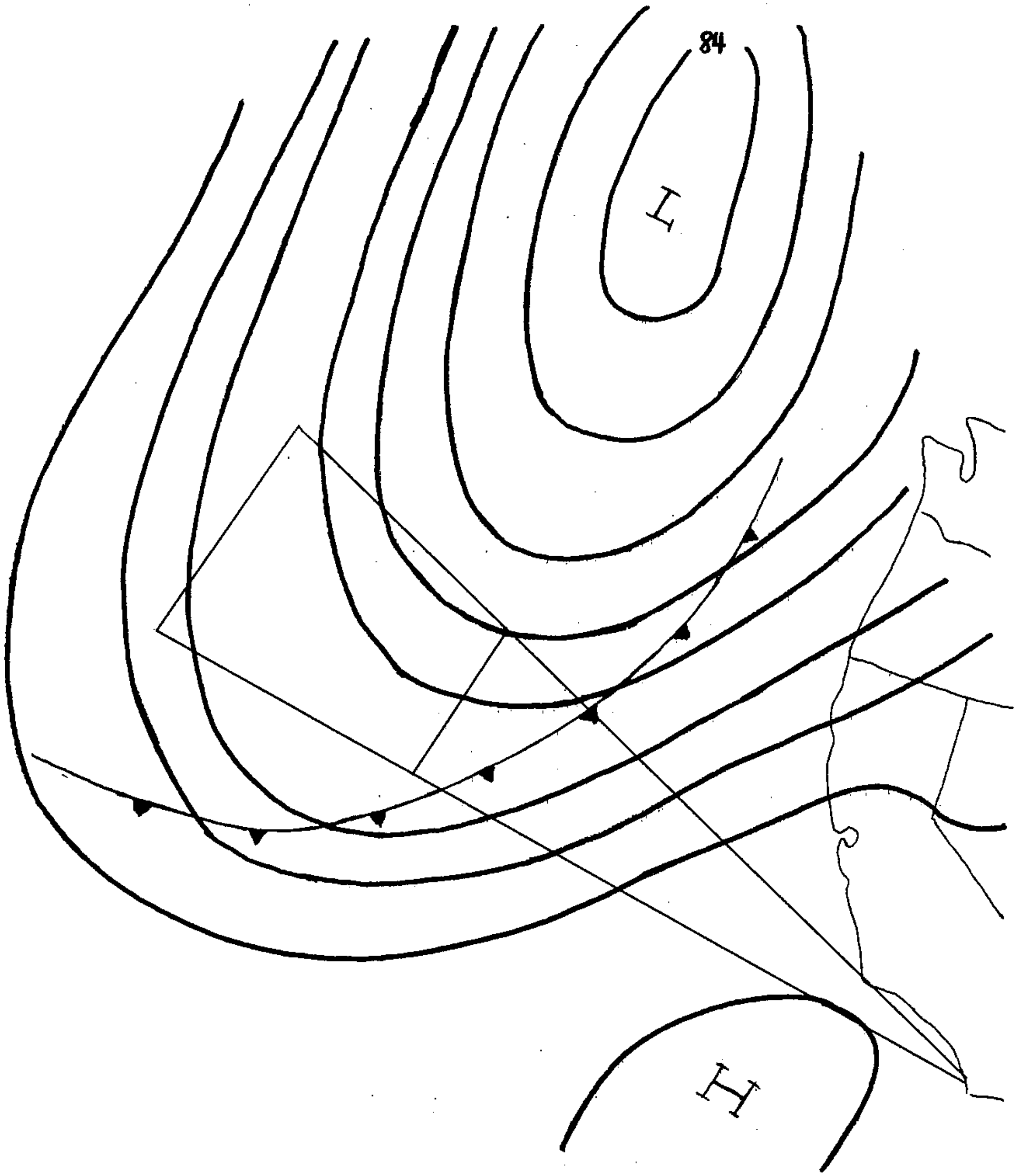


Figure 9. Chart for North Pacific Storm.

CHART DATE: 11/09/0600 GMT/1871

FETCH:

Windspeed in fetch:	30 kts
Length of fetch:	360 nm
Duration of fetch:	24 hrs
Decay distance:	950 nm

SMB CALCULATIONS:

Sea height:	15 ft
Sea period:	8.5 secs
Swell height:	4.5 ft
Swell period:	11 secs
Travel time:	60 hrs
ETA:	11/1000 PST

PNJ CALCULATIONS:

Wave group energy: 58 ft^2

Upper limit period: 16.7 secs

Lower limit period: 0.0 secs

Significant height: 21.5 ft

Range of approach: -3 to -15 deg

Angular spreading factor: 12.5%

Travel time of leading wave: 36 hrs

ETA: 10/1000 PST

Decay Table:

Date/time	Shortest Period	Spectrum Energy	Significant Wave Height
10/1600	14.1	10	3.
2200	12.2	16	4.
11/0400	11.0	25	4.8
1000	9.8	32	5.5
1600	9.0	26	5.0
2200	8.2	26	5.0

Figure 10. Sea state forecast calculations for North Pacific Storm.

DAY/TIME PST	I	II	III	IV	V	VI	VII	VIII	T	H1/3 (ft)	H/10 (ft)	H_M (ft)	$\overline{T}$ (secs)
10/00	.9	.7	.5	.8	1.2	1.6	1.2	.9	7.8				
03	2.6	2.7	1.5	1.3	1.5	1.7	1.4	.9	13.6				
06	2.2	4.3	3.3	2.9	1.4	1.5	1.3	1.0	17.9				
09	3.3	5.5	7.5	3.2	2.5	2.3	2.0	1.1	27.4	3.4	4.0	4.2	18.5
12	3.3	5.9	9.5	7.5	4.0	2.3	2.1	1.4	36.0	4.0	5.5	6.2	16.5
15	3.0	5.3	7.5	7.5	5.3	4.0	2.7	1.8	37.1				
18	3.0	5.0	8.9	9.9	6.0	4.0	2.7	2.0	41.5				
21	2.9	4.3	7.3	9.5	7.2	5.5	3.5	2.4	42.5	5.6	6.8	8.5	13.7
11/00	2.4	4.0	7.0	9.0	7.6	5.5	3.5	2.4	41.4				
03	1.4	3.6	6.3	9.9	7.6	5.2	3.6	2.4	40.0				
06	2.3	3.3	5.8	9.4	7.2	5.5	3.7	2.2	39.4	5.0	6.7	9.3	13.2
09	3.5	4.0	5.2	8.0	6.8	5.6	3.7	2.3	39.1				
12	1.8	2.2	3.2	5.5	5.2	5.0	3.5	2.0	28.4	4.0	4.8	7.3	12.8
15	2.0	4.0	2.6	4.0	5.0	4.2	2.8	2.0	26.6				
18	1.5	2.0	2.2	3.6	4.5	3.8	2.7	2.0	22.2				
21	1.2	1.3	1.6	2.7	3.1	3.4	2.5	1.8	17.6				
12/00	0.8	1.2	1.5	2.8	3.0	3.2	2.8	1.8	17.1				

Figure 11. Analyzer trace for North Pacific storm and corresponding wave records.

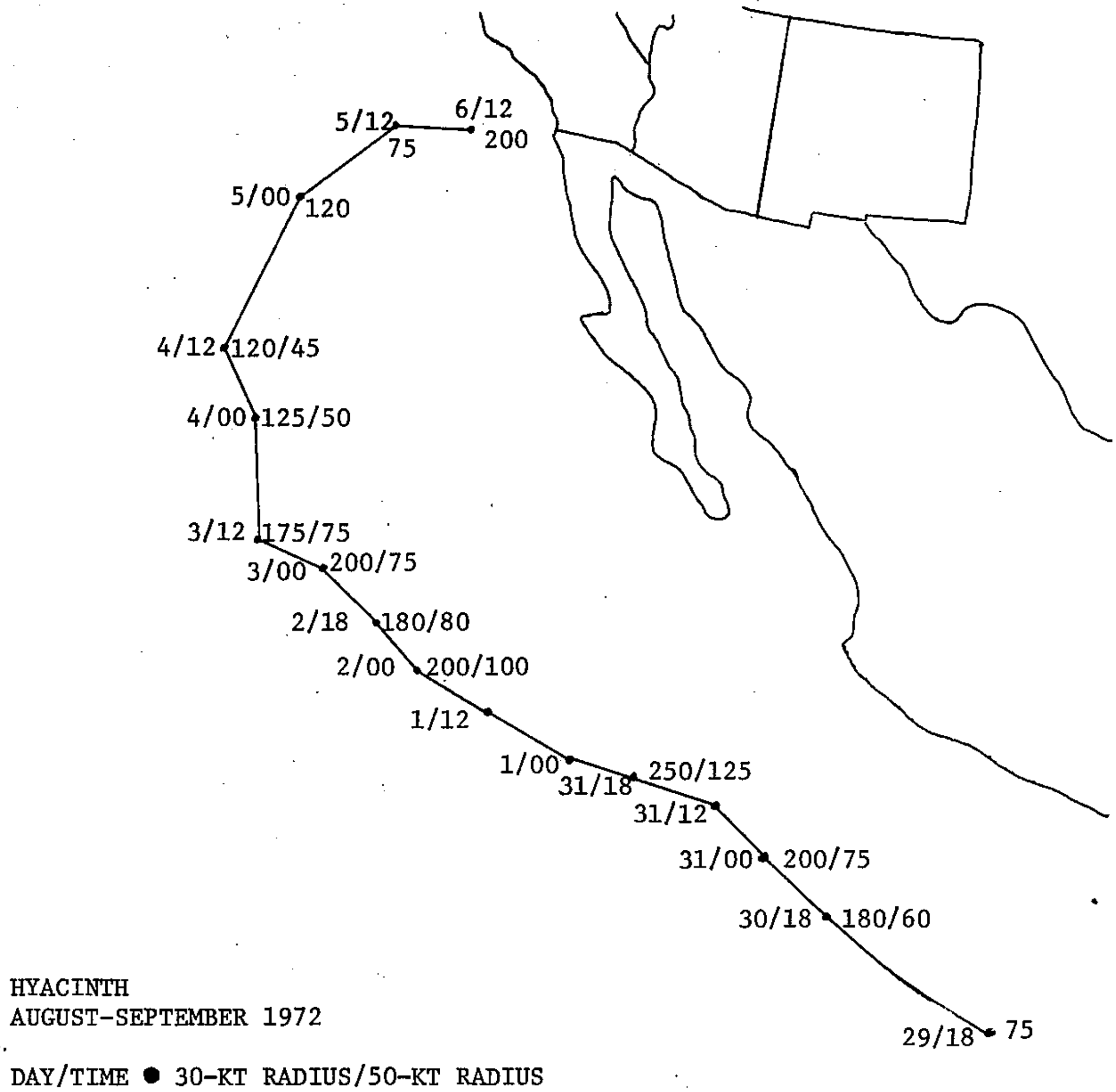


Figure 12. Track of Hurricane Hyacinth.

HYACINTH SEPTEMBER 1972

										ft			secs
DAY/TIME PST	I	II	III	IV	V	VI	VII	VIII	T	H1/3 (H_b)	H1/10	H_M	$\overline{T}$
02/00	.3	.3	.5	.5	.8	1.0	.6	.5	4.5				
03	.3	.3	.4	.6	.9	1.2	.9	.6	5.2				
06	.4	.5	.5	.7	.8	1.2	1.0	.6	5.7	.6	1.1	1.3	13.3
09	.7	.7	.7	1.0	1.0	1.4	1.3	1.0	7.8				
12	.7	.7	.7	1.1	1.2	1.5	1.5	1.7	9.1	2.7	3.3	4.1	12.5
15	1.0	1.5	1.4	1.6	2.0	2.1	2.0	1.8	13.4				
18	1.2	1.0	1.0	1.2	1.9	3.0	3.0	1.8	14.1				
21	1.0	.7	.8	1.1	1.6	2.7	3.0	1.5	12.4	2.7	3.3	4.6	12.8
03/00	.6	.5	.5	.8	1.4	2.5	3.4	2.0	11.7				
03	.5	.5	.5	.9	1.4	2.5	4.0	2.8	13.1				
06	.5	.5	.5	.9	1.1	1.5	2.3	2.7	10.0	2.3	2.8	3.5	12.8
09	.5	.5	.5	1.0	1.2	1.4	1.6	2.7	9.4	4-6			
12	.5	.5	.5	.8	1.0	1.1	1.2	1.8	7.4	1.9	2.5	2.9	11.8
15	.8	.7	.7	1.0	1.3	1.2	1.1	1.5	8.3	4-7			
18	.8	.7	.7	1.2	1.5	1.6	1.3	1.2	9.0				
21	.7	.6	.6	.9	1.2	1.3	1.2	1.1	7.8	1.7	1.8	1.8	12.5
04/00	.4	.4	.4	.8	1.1	1.1	1.1	1.0	6.4				
03	.6	.4	.4	.7	1.1	1.5	1.6	1.0	7.3				
06	.5	.5	.5	.8	1.8	1.8	.9	1.6	7.9	1.4	2.3	2.4	12.5
09	.6	.6	.6	.7	1.1	1.5	1.5	2.0	8.6				
12	.6	.5	.5	.6	.9	1.4	1.4	1.8	7.7	1.4	2.2	2.6	12.8
15	.6	.6	.6	.7	.8	1.2	1.2	1.5	6.5				
18	.7	.7	.6	.7	1.0	1.5	1.5	1.5	8.2				
21	.7	.6	.6	.9	1.1	1.3	1.2	1.1	7.5	m			
05/00	.4	.4	.4	.8	1.1	1.2	1.1	1.0	6.4				
03	.5	.4	.4	.7	1.4	1.4	1.4	1.0	7.2				
06	.5	.5	.5	.7	1.3	1.8	1.9	1.6	8.8	2.1	2.7	3.6	10.2
09	.5	.5	.5	.7	1.1	1.5	1.5	2.0	8.3				
12	.5	.5	.5	.6	.9	1.4	1.4	1.8	7.6	1.8	2.3	3.0	11.0
15	.6	.6	.6	.6	.8	1.1	1.1	1.5	6.9				
18	.6	.6	.6	.6	1.0	1.4	1.4	1.4	7.6				
21	.5	.5	.5	.5	.7	1.2	1.2	1.0	6.1	m			
06/00													
03													
06										1.5	2.3	3.8	9.4
09													
12										1.1	1.6	2.1	9.4

Figure 13. Analyzer trace for Hurricane Hyacinth and corresponding wave records.

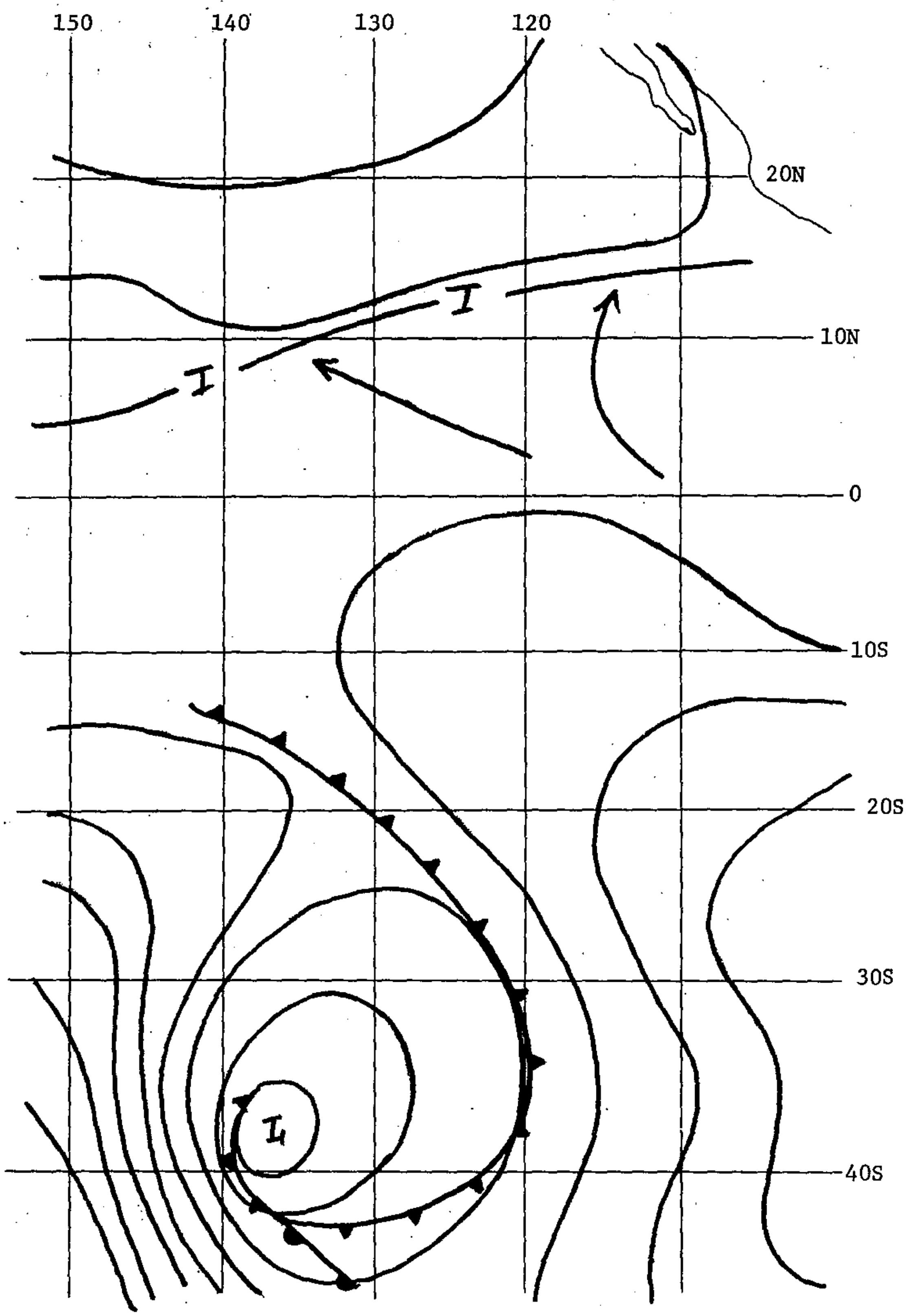


Figure 14. Chart for Southern Hemisphere Storm, August 9, 1973.

SOUTHERN HEMISPHERE AUGUST 1973

DAY/TIME PST	I	II	III	IV	V	VI	VII	VIII	T	H1/3 (H_b) g ft	H1/10	H_M	T secs	
14/18	.6	.8	.8	.9	.8	.8	.8	.8	6.3					
21	.7	1.0	1.0	1.4	1.0	.8	.8	.8	7.5					
15/00	.6	1.1	1.0	1.4	1.1	.8	.8	.8	7.6					
03	1.3	1.3	1.4	2.0	1.4	1.0	.8	.8	10.0					
06	.8	1.0	1.2	1.3	1.2	1.0	.8	.8	8.1					
09	.8	1.1	1.6	1.6	1.7	1.1	.8	.8	9.5					
12	.8	1.0	1.4	1.6	1.8	1.4	.9	.7	9.6					
15	.8	.9	1.5	1.8	1.9	1.5	.9	.7	10.0					
18	1.0	1.0	1.4	1.9	1.9	1.6	.9	.7	10.4					
21	.7	.7	1.2	1.8	1.7	1.5	.9	.7	9.2					
16/00	.7	.8	1.1	2.1	2.0	1.8	1.0	.7	10.2					
03	.7	.7	1.0	2.2	2.2	1.9	1.0	.7	10.4					
06	.5	.5	.8	1.7	1.7	1.7	1.2	.8	9.1	1.5	1.7	1.9	15.0	
09	.7	.7	.8	1.6	1.9	1.8	1.2	.7	9.4	6	5	5	4 4	5
12	.6	.7	.9	1.8	2.1	2.0	1.3	.7	10.1	1.5	2.0	2.2	15.7	
15	.9	.9	.9	1.8	2.1	2.1	1.5	.8	11.0					
18	missing													
21	.6	.7	.8	1.6	1.7	1.9	1.3	.8	9.4	1.9	2.0	2.3	15.4	
17/00	.6	.6	.7	1.5	2.3	2.0	1.5	.7	9.9					
03	.6	.6	.6	1.2	2.0	2.0	1.5	.7	9.2					
06	.6	.6	.6	1.0	1.7	1.7	1.3	.7	8.2	1.2	1.4	1.7	14.3	
09	.5	.6	.7	1.1	1.7	1.7	1.4	.8	8.5	5	4	4	5 6	3
12	.5	.7	.8	1.1	2.0	2.0	1.5	.8	9.4	1.3	1.7	2.1	13.7	
15	.6	.6	.6	1.0	1.7	2.1	1.6	.8	9.1					
18	.6	.6	.6	1.0	1.7	2.1	1.6	.8	9.0					
21	.6	.6	.6	.8	1.5	2.0	1.5	.8	8.4	1.3	1.7	2.3	13.3	
18/00	.6	.6	.6	.8	1.5	2.0	1.4	.8	8.3					
03	.6	.6	.6	.7	1.1	1.6	1.4	.8	7.4					
06	.6	.6	.6	.7	1.0	1.5	1.5	.8	7.3	1.2	1.9	2.4	13.8	
09	.6	.7	.7	.8	1.0	1.6	1.6	1.8	7.8					
12	.6	.7	.8	.8	.9	1.7	1.7	.8	8.0	1.0	1.8	2.0	13.6	
15	1.0	1.0	1.0	1.0	1.0	1.7	1.7	1.0	9.4					
18	.5	.6	.6	.7	.8	1.3	1.3	.8	6.6					
21	.4	.6	.6	.6	.8	1.2	1.2	.8	6.2	1.1	1.3	1.5	13.5	
19/00	.5	.6	.7	.7	.8	1.0	1.2	.8	6.3					
03	.7	.7	.7	.7	.8	.9	1.1	.8	6.4					
										.7	1.0	1.2	13.3	
										2	2	2	1 4	3

Figure 15. Analyzer trace for Southern Hemisphere storm and corresponding wave records.

92 Smoke Management in the Willamette Valley. Earl M. Bates, May 1974. (COM-74-11277/AS)
93 An Operational Evaluation of 500-mb Type Stratified Regression Equations. Alexander E. MacDonald, June 1974. (COM-74-11407/AS)
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